Current Performance of RHIC at Low Energies

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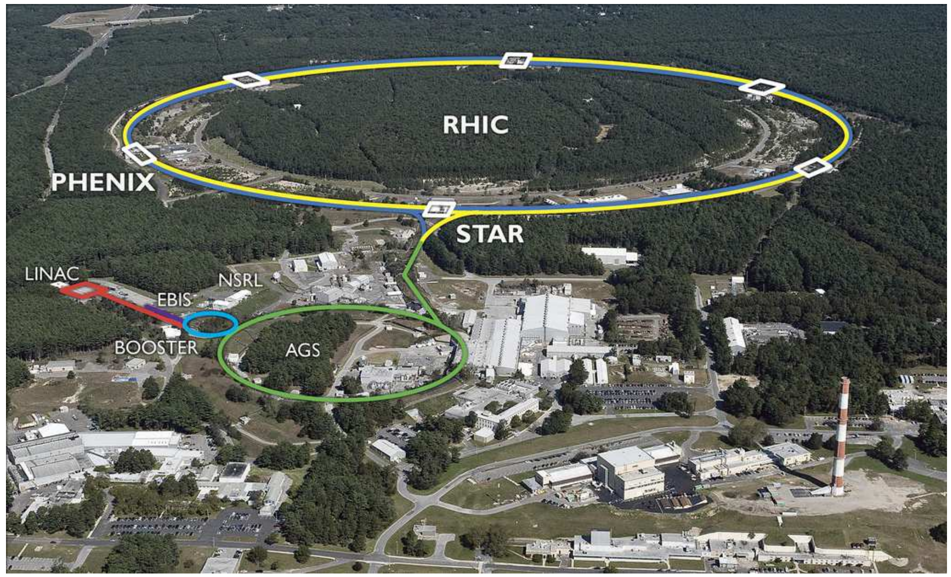
The Relativistic Heavy Ion Collider



Circumference: $C = 3833.845\,\mathrm{m}$

Nominal Au beam energy range: $E = 10\,\mathrm{GeV/n}$–$100\,\mathrm{GeV/n}$

Required beam energy range for critical point search:

$E = 2.5\,\mathrm{GeV/n} - 15\,\mathrm{GeV/n}$

Energy range for critical point search is (well) below design energies

Known Challenges at Low Energy

- Transverse beam size
- Space charge
- Intrabeam scattering
- Magnet nonlinearities

Transverse Beam Size

At any location s around the circumference of the machine, the rms transverse beam size is calculated as

$$\sigma = \sqrt{\epsilon\beta(s)},$$

with

$$\epsilon\gamma = \epsilon_N \qquad \text{(normalized emittance)}$$

The lower the energy, the larger the beam size – aperture problem

$$\begin{aligned} \text{Luminosity}\, L &\propto \beta_{\text{IP}}^{-1} \\ \beta_{\text{IP}} \cdot \beta_{\text{triplet}} &\approx \text{const.} \end{aligned}$$

Luminosity limit

Space Charge

Space charge tune shift

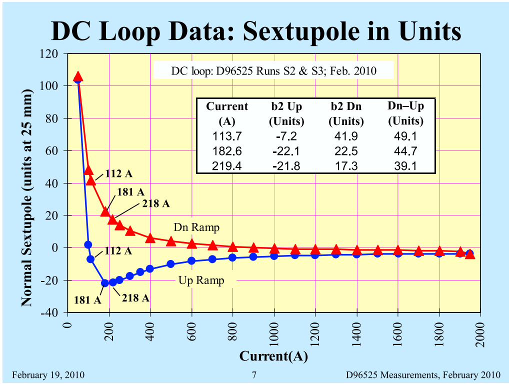
$$\Delta Q_{\mathrm{sc}} = -\frac{Z^2 r_p}{A} \frac{N}{4\pi\beta\gamma^2\epsilon_N} \frac{C}{\sqrt{2\pi}\sigma_s}$$

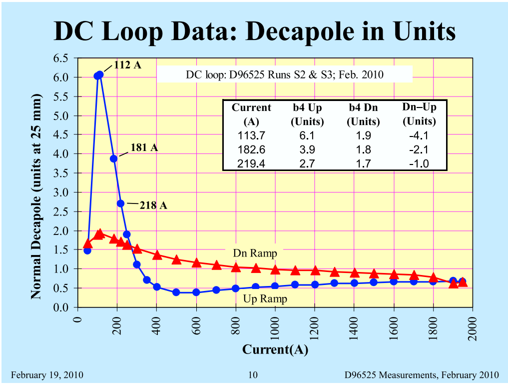
The large machine circumference C of RHIC results in large space charge tune shift at low energy

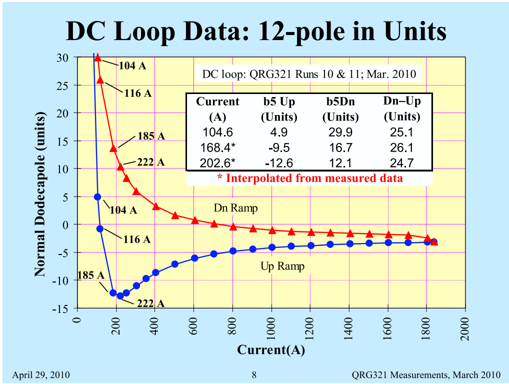
Space charge tune spread has to fit in-between low-order nonlinear resonances

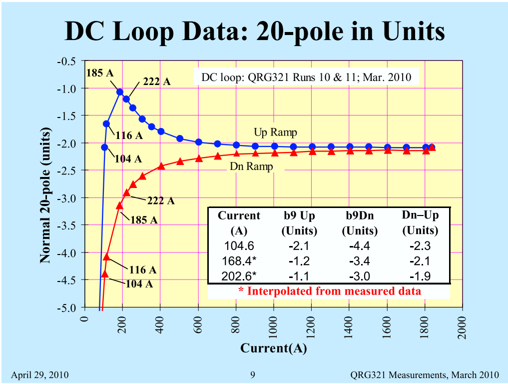
Space charge limit in RHIC experimentally determined at $\Delta Q_{\mathrm{sc}} \approx -0.05$

Magnet Nonlinearities









Magnets are optimized at full field; nonlinearities are worst in region interesting for critical point search

Achieved Beam Parameters at Low Energy

	2.5 GeV	3.85 GeV	5.75 GeV
γ	2.68	4.1	6.1
σ_s [m]	2.5	1.5	1.5
ϵ_n [mm mrad]	20 (?)	20	15
I_{bunch} [1e9]	0.05	0.5	1.1
N_{bunches}	27	111	111
β^* [m]	8.5	6.0	6.0
ΔQ_{bb}	1.2e-4	1.2e-3	1.7e-3
ΔQ_{sc}	0.005	0.035	0.047
$\tau_{\text{IBS}}(x/s)$ [sec]		475/525	4350/330
τ_{beam} [sec]	250	1000	1500
τ_{lumi} [sec]	?	400	1500
L_{peak} [cm^{-2}sec^{-1}]	> 0	3.1e24	3.3e25
$L_{\text{store avg.}}$ [cm^{-2}sec^{-1}]	> 0	1.25e24	1.5e25

Without electron cooling, BES-II would take about 70 weeks

Performance at 2.5 GeV not sufficient for physics

RF Frequency and Harmonic Number

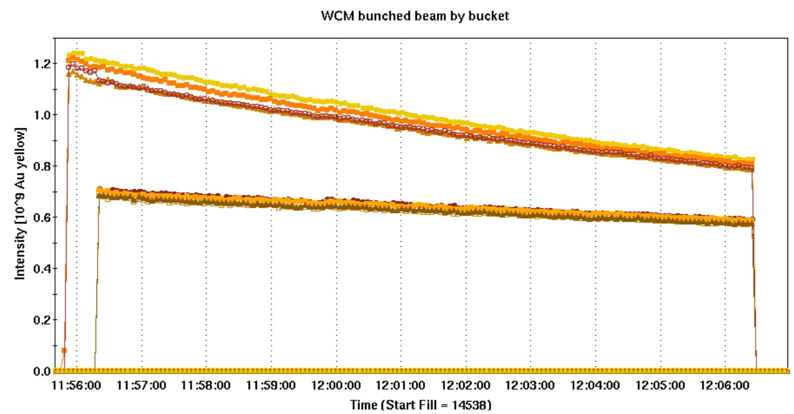
Limited RF frequency range requires larger harmonic numbers at low energy

E_{tot} [GeV/nucleon]	$\sqrt{s_{\mathrm{NN}}}$ [GeV]	Harmonic number	No of simultaneous experiments
2.42-2.55	4.84-5.10	387	2
2.55-2.67	5.10-5.34	384	1
2.67-2.84	5.34-5.68	381	1
2.84-3.08	5.68-6.16	378	2
3.08-3.32	6.16-6.64	375	1
3.32-3.69	6.64-7.38	372	1
3.69-4.33	7.38-8.66	369	2
4.33-5.17	8.66-10.34	366	1
5.17-7.30	10.34-14.60	363	1
7.30-100	14.60-200	360	2

Only in select energy ranges collisions can be provided to both experiments

5.75 GeV

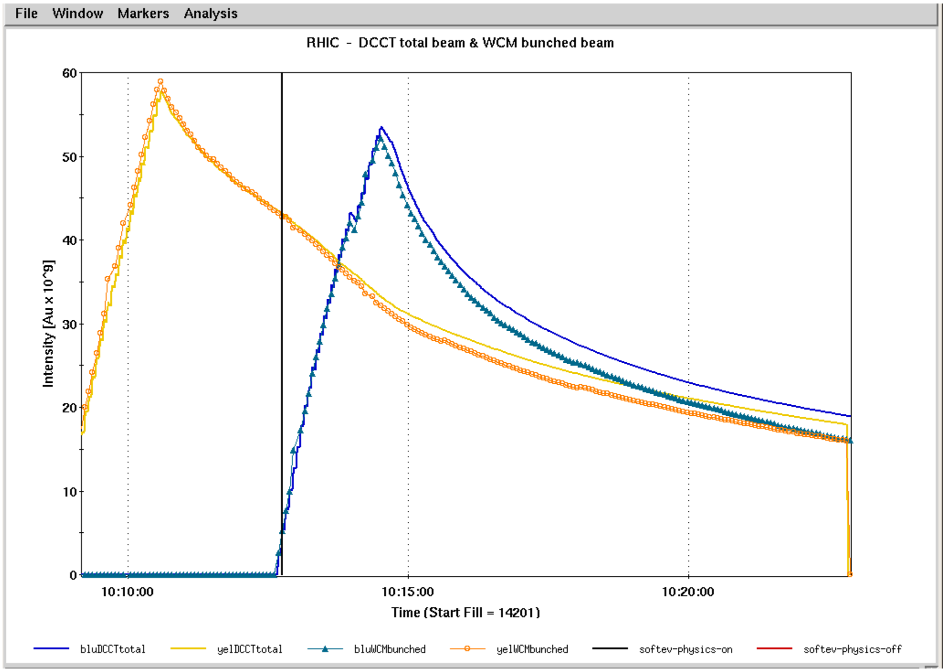
Lifetime without collisions



- 1600 sec lifetime for 98 percent of the beam at $1.1 \cdot 10^9$
- 4200 sec lifetime for 93 percent at $0.7 \cdot 10^9$

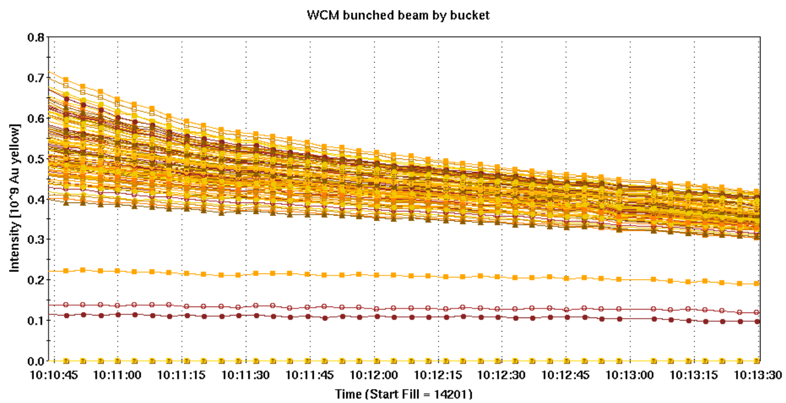
Very good agreement with IBS simulations

3.85 GeV



- Intensity limited to $0.7 \cdot 10^9$ per bunch by poor lifetime at full intensity; likely space charge limit

Lifetime dependence without collisions

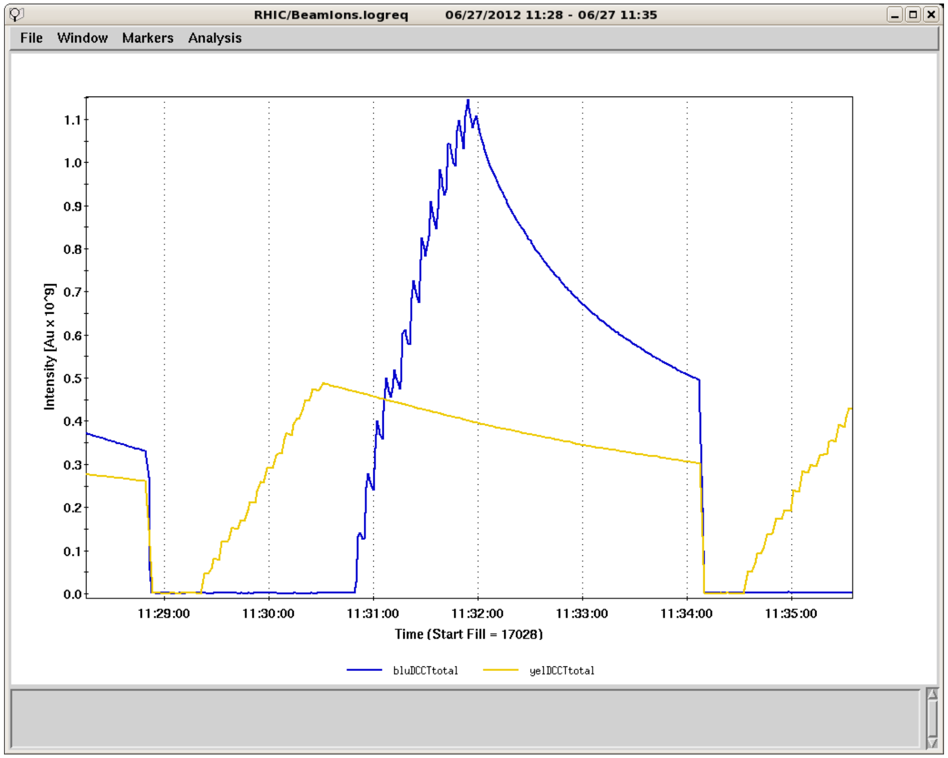


Double-exponential fit:

- $\tau_{\text{fast}} = 30\,\text{sec}$ for 18 percent of the beam, $\tau_{\text{slow}} = 500\,\text{sec}$ for 82 percent of the beam, at $N = 0.73 \cdot 10^9$, $\Delta Q_{\text{sc}} = 0.1$
- $\tau = 1000\,\text{sec}$ at $N = 0.26 \cdot 10^9$, $\Delta Q_{\text{sc}} = 0.04$ (single exponential fit)

Good agreement with IBS simulations; strong dependence on collimator setting (aperture)

2.5 GeV



27 bunches, $\approx 4\,\mathrm{min}$ lifetime

Blue bunch intensity $N = 4 \cdot 10^7$

Filling 111 bunches takes about $2\,\mathrm{min}$ per beam – need 3 times longer lifetime to be efficient

- Tiny intensity due to poor injection efficiency - only 90 percent. Not understood yet.

- Bunches out of AGS are extremely long, even longer than the injection kicker pulse

- Transverse beam sizes are unknown; RHIC instrumentation does not work properly at these intensities

- 4 min beam lifetime is reasonable, but space charge effects at nominal intensity may change that

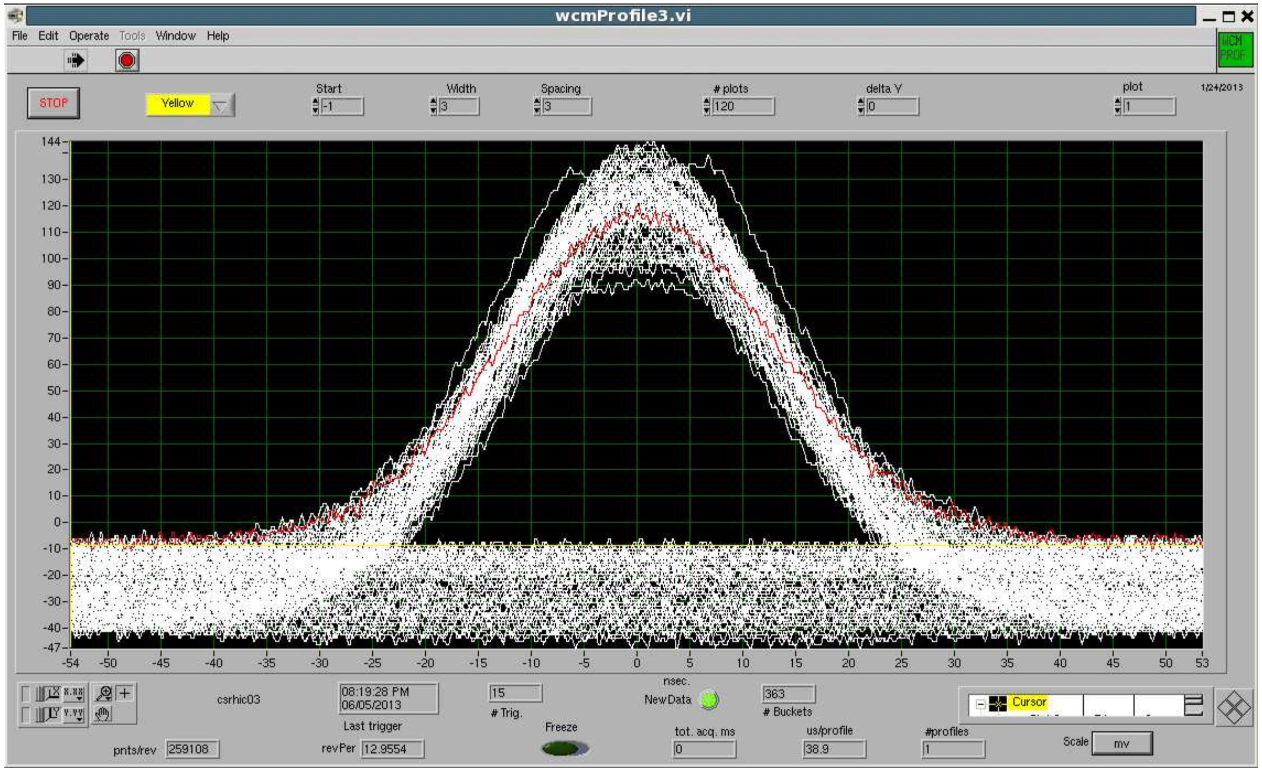
Understanding the Performance at 2.5 GeV

Objective: Test single-particle effects by using protons instead of gold in the same lattice
Parameters:

ramp	pp13-6GeV
$B\rho$	19.3 Tm
E	5.86 GeV
E_{kin}	4.92 GeV
γ	6.25
p	5.79 GeV/c
f_{rev}	77.187 kHz
h	363

Higher γ at the same $B\rho$ as gold results in smaller beam sizes, less space charge and IBS

Longitudinal bunch profile

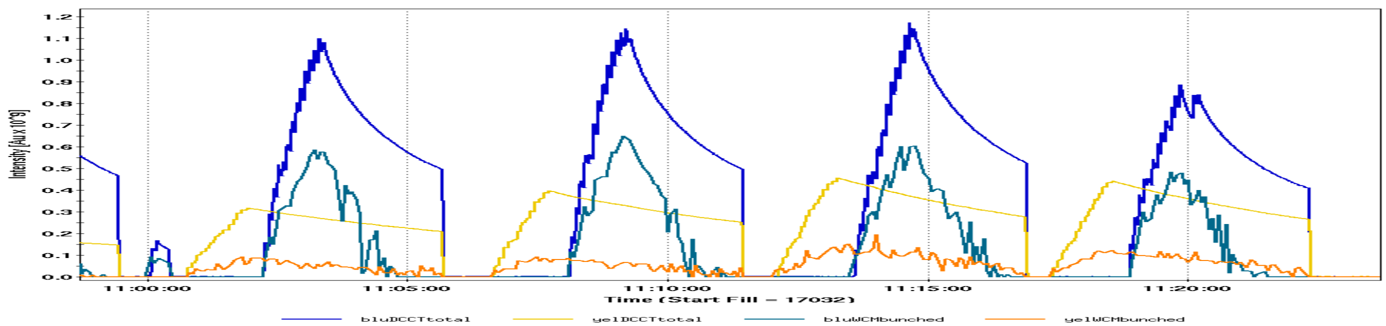


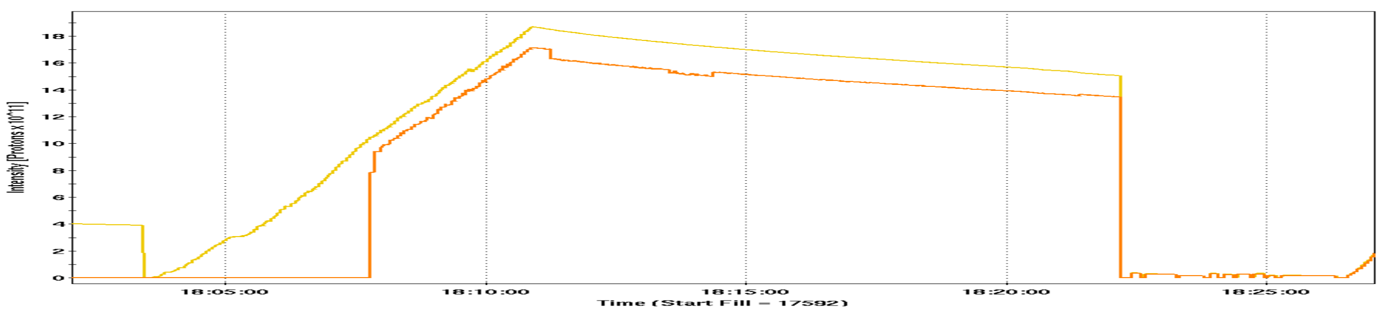
$\sigma_s = 3\,\mathrm{m}$

22 kV on 9 MHz in RHIC, 33 kV in AGS

$f_s = 100\,\mathrm{Hz}$, $\Delta p/p = 2.7 \cdot 10^{-4}$

Beam intensities with gold (top) and protons (bottom)





Stores during 25 min of beam operation

50 percent injection efficiency with protons, vs. 10 percent with gold

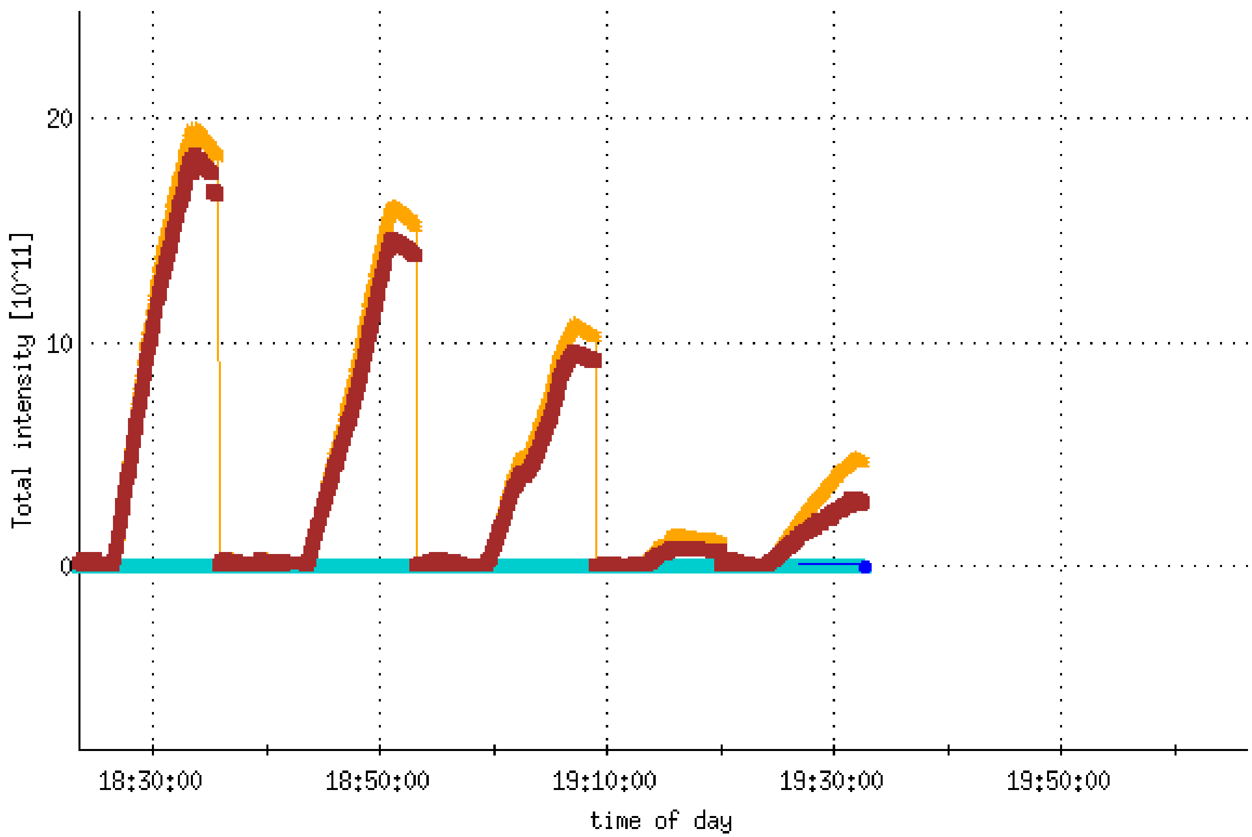
Dynamic aperture measurements

Two methods:

- Inject beam with intentional offset, measure acceptance with polarimeter

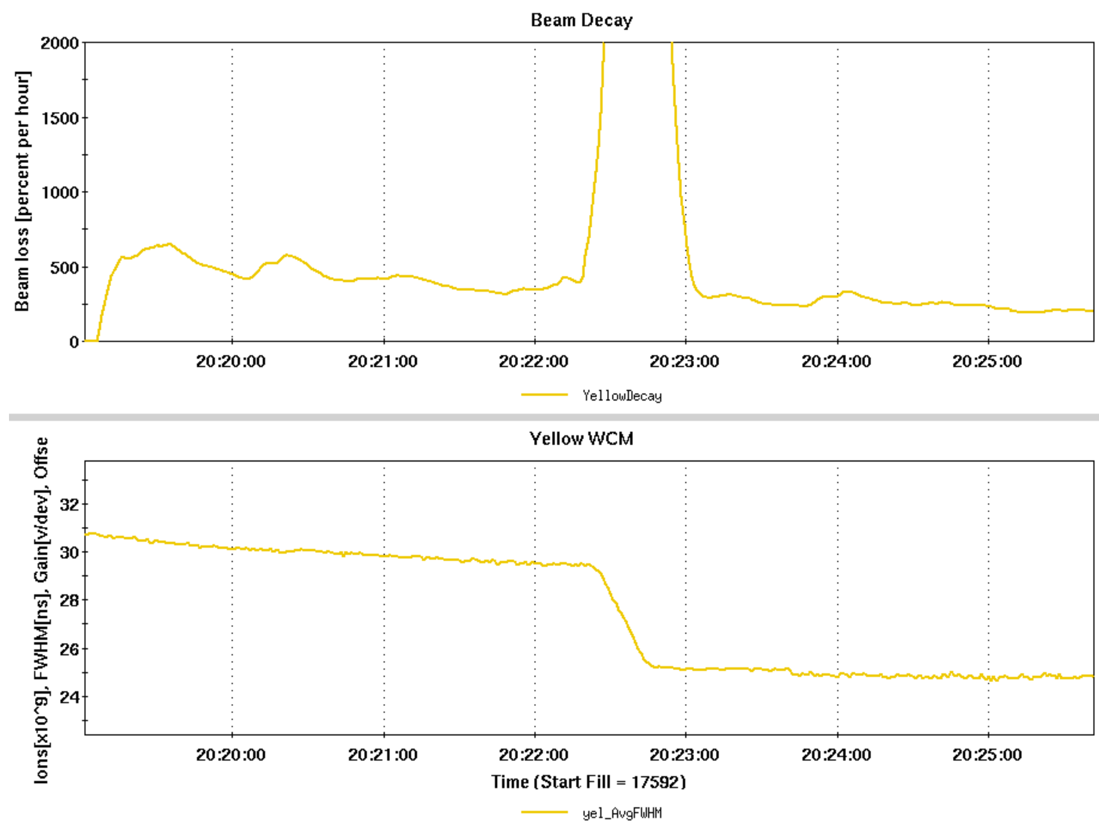
- Blow-up emittance with BBQ, measure maximum beam profiles with polarimeter

Intensities with mis-steered injection



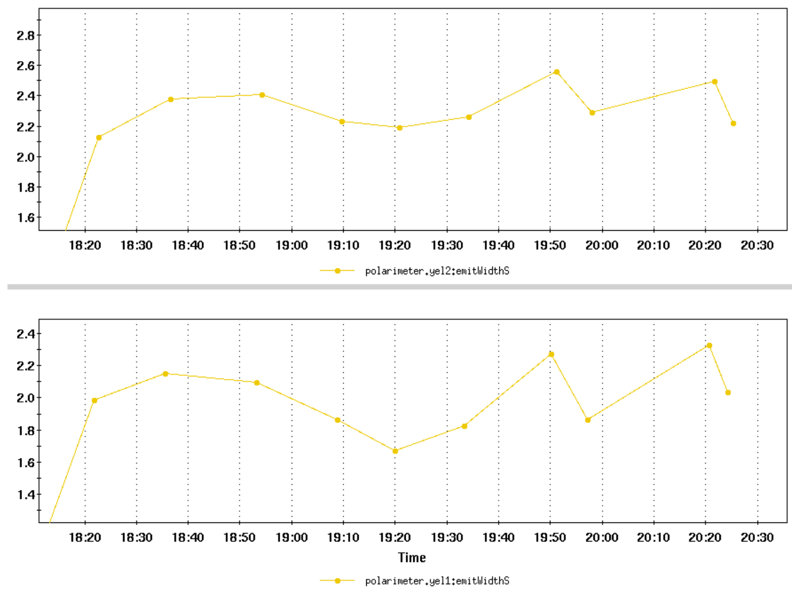
Intensity suffers due to mis-steering

Beam decay and bunch length during blow-up with BBQ



Beam decay immediately recovers when BBQ is turned off
Bunch length shrinks during kicking
$\Rightarrow$ off-momentum dynamic aperture limitation

RMS beam sizes during DA measurement



RMS beam size remains unchanged regardless of mis-steering and BBQ blow-up efforts

$\Rightarrow$ (Dynamic) aperture is already filled anyway, RMS emittance (=acceptance) $\epsilon = 0.16\,\mathrm{mm\,mrad}$

(or normalized $\epsilon_n = 1\,\mathrm{mm\,mrad}$)

Space charge

Space charge tune shift:

$$\Delta Q_{\mathrm{sc}} = -\frac{Z^2 r_p}{A} \frac{N}{4\pi\beta\gamma^2\epsilon_n} \frac{C}{\sqrt{2\pi}\sigma_s}$$

With $Z = A = 1$, $N = 4 \cdot 10^{10}$, $\epsilon_n = 1\,\mathrm{mm\,mrad}$, and $\sigma_s = 3\,\mathrm{m}$, this results in a space charge tune shift of

$$\Delta Q_{\mathrm{sc}} = -0.065$$

For 2.5 GeV gold at the same emittances ($\epsilon_n = 0.4\,\mathrm{mm\,mrad}$ due to smaller γ), this tune shift would be reached at $N_{\mathrm{Au}} = 8 \cdot 10^7$

Beam-beam tuneshift would be $\xi_{\mathrm{IP}} = 8 \cdot 10^{-4}$

This would allow for a peak luminosity of $2 \cdot 10^{22}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

Intrabeam Scattering

Calculated IBS rates for:

1. protons with $N = 4 \cdot 10^{10}$, $\epsilon_n = 1\,\mathrm{mm\,mrad}$, and $\sigma_s = 3\,\mathrm{m}$, $\tau = 1030\,\mathrm{sec}$ - seems consistent with measured beam lifetime

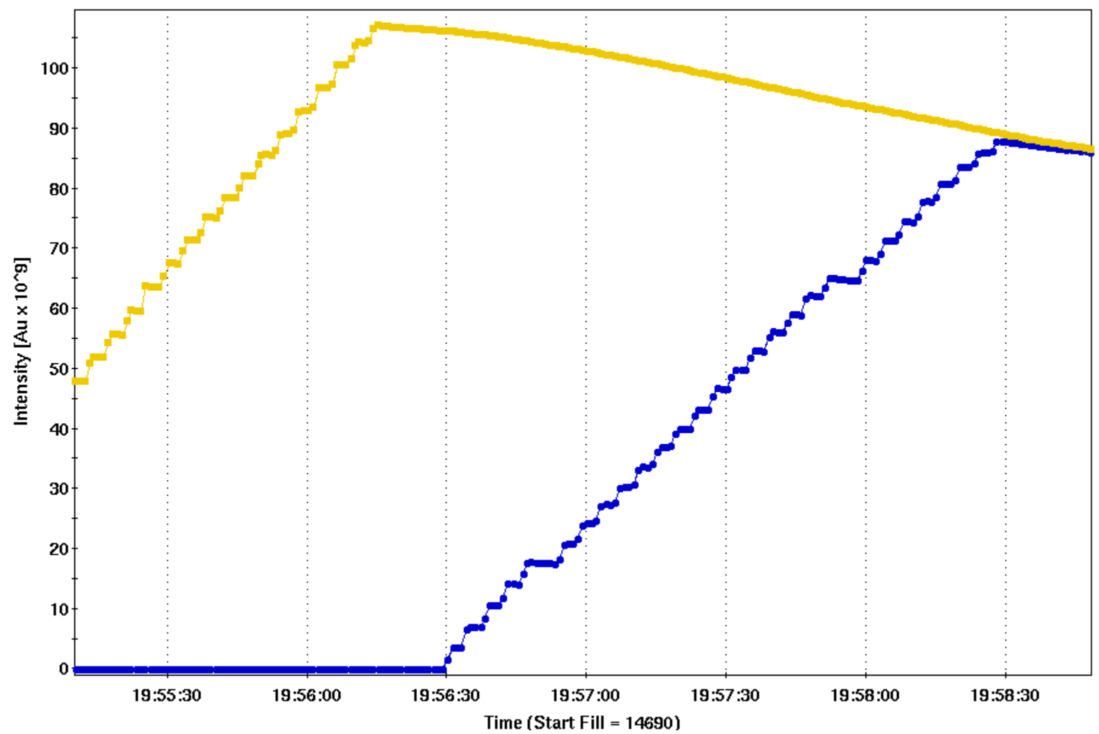
2. gold with $N = 4 \cdot 10^7$, $\epsilon_n = 0.4\,\mathrm{mm\,mrad}$, and $\sigma_s = 3\,\mathrm{m}$: $\tau = 120\,\mathrm{sec}$ - may be consistent with measured lifetime, assuming beam was bunched

3. gold with $N = 8 \cdot 10^7$, $\epsilon_n = 0.4\,\mathrm{mm\,mrad}$, and $\sigma_s = 3\,\mathrm{m}$: $\tau = 60\,\mathrm{sec}$ - guideline for cooler design

Lifetime simulations with aperture limit at 3σ underway

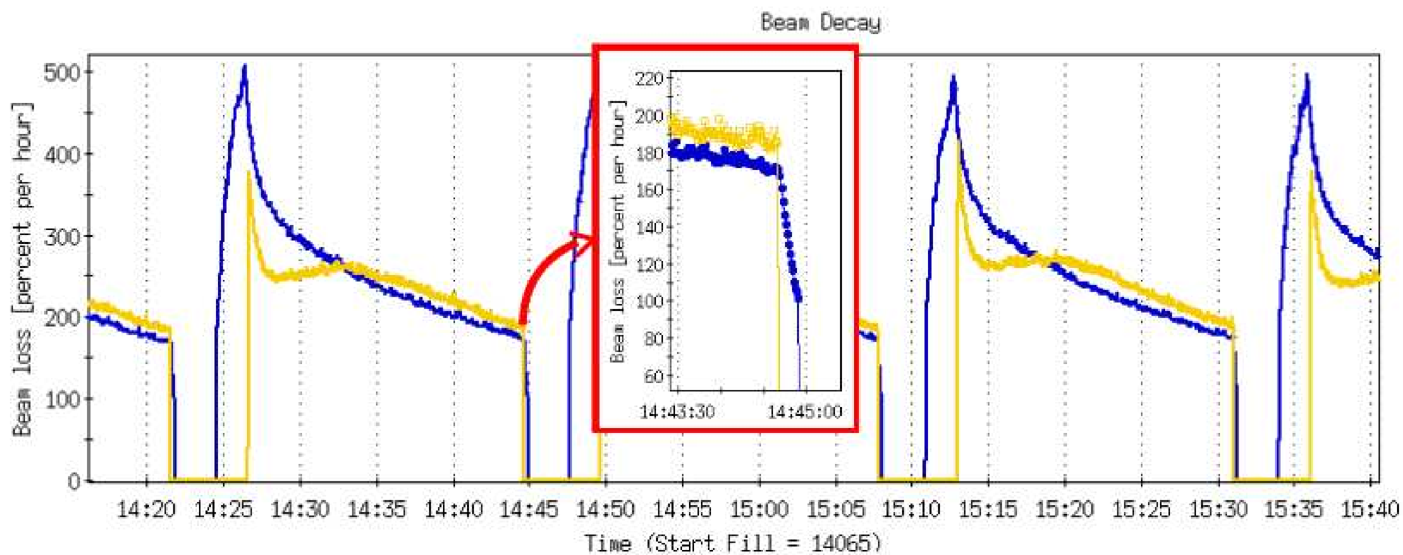
Beam-beam

Beam intensities at the start of a 5.75 GeV store



Yellow lifetime deteriorates as Blue is filled (beams are always in collision)

Beam decay rate at 5.75 GeV

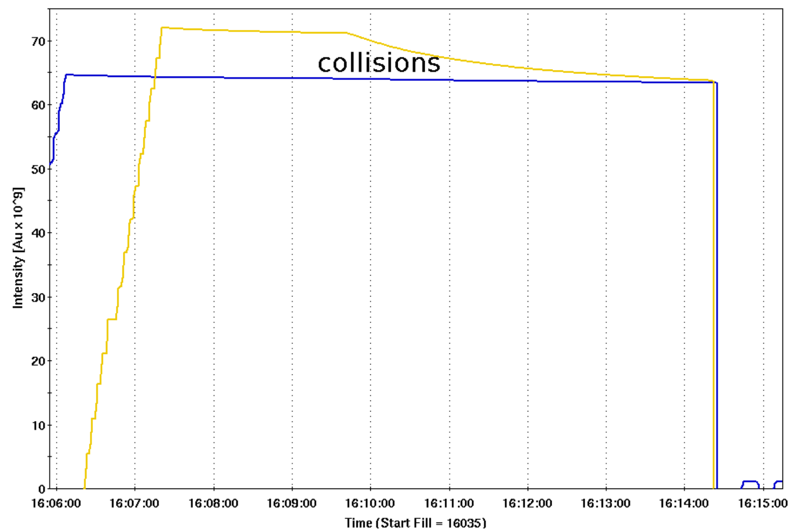


Blue beam decay improves dramatically as soon as Yellow is dumped at the end of store

Though $\xi_{\text{beam-beam}} << \Delta Q_{\text{SC}}$, beam-beam has a strong effect on beam lifetime

Intensities at near-integer tunes (APEX)

Near the integer, spacing between nonlinear resonances is largest



Blue tunes: $(Q_x/Q_y) = (.09/.07)$ (below diagonal)
Yellow tunes: $(Q_x/Q_y) = (.08/.09)$ (above diagonal)
No observable beam-beam effect in the Blue ring, with $\Delta Q_{\rm sc} = -0.03$, $\xi_{\rm beam-beam} = -0.002$

Summary

- Beam lifetime without collisions consistent with IBS - can be counteracted by electron cooling

- Unexpectedly strong beam-beam effects limit lifetime in collision; maybe overcome at near-integer tunes

- Performance at lowest energy (2.5 GeV) still under study